Summary of Results from the SLAC ESTB T-506 Irradiation Study

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UCSC/SCIPP

FCAL Collaboration
High precision design

T-506 Motivation

BeamCal maximum dose ~100 MRad/yr

BeamCal is sizable: ~2 m^2 of sensors.

A number of ongoing studies with novel sensers: GaAs, Sapphire, SiC

➔ Are these radiation tolerant?

➔ Might mainstream Si sensors in fact be adequate?

Radiation Damage in Electromagnetic Showers

Folk wisdom: Radiation damage proportional to non-ionizing component of energy loss in material ("NIEL" model)

BeamCal sensors will be embedded in tungsten radiator

Energy loss dominated by electromagnetic component but non-ionizing contribution may be dominated by hadronic processes

Hadronic Processes in EM Showers

There seem to be three main processes for generating hadrons in EM showers (all induced by **photons**):

• Nuclear ("giant dipole") resonances

Resonance at 10-20 MeV (~$E_{critical}$)

• Photoproduction

Threshold seems to be about 200 MeV

• Nuclear Compton scattering

Threshold at about 10 MeV; Δ resonance at 340 MeV

➔ These are largely isotropic; must have most of hadronic component develop near sample

T-506 Idea

Embed sample sensors in tungsten:

“Pre-radiator” (followed by ~50 cm air gap) spreads shower a bit before photonic component is generated

“Post-radiator” brings shower to maximum just before sensor

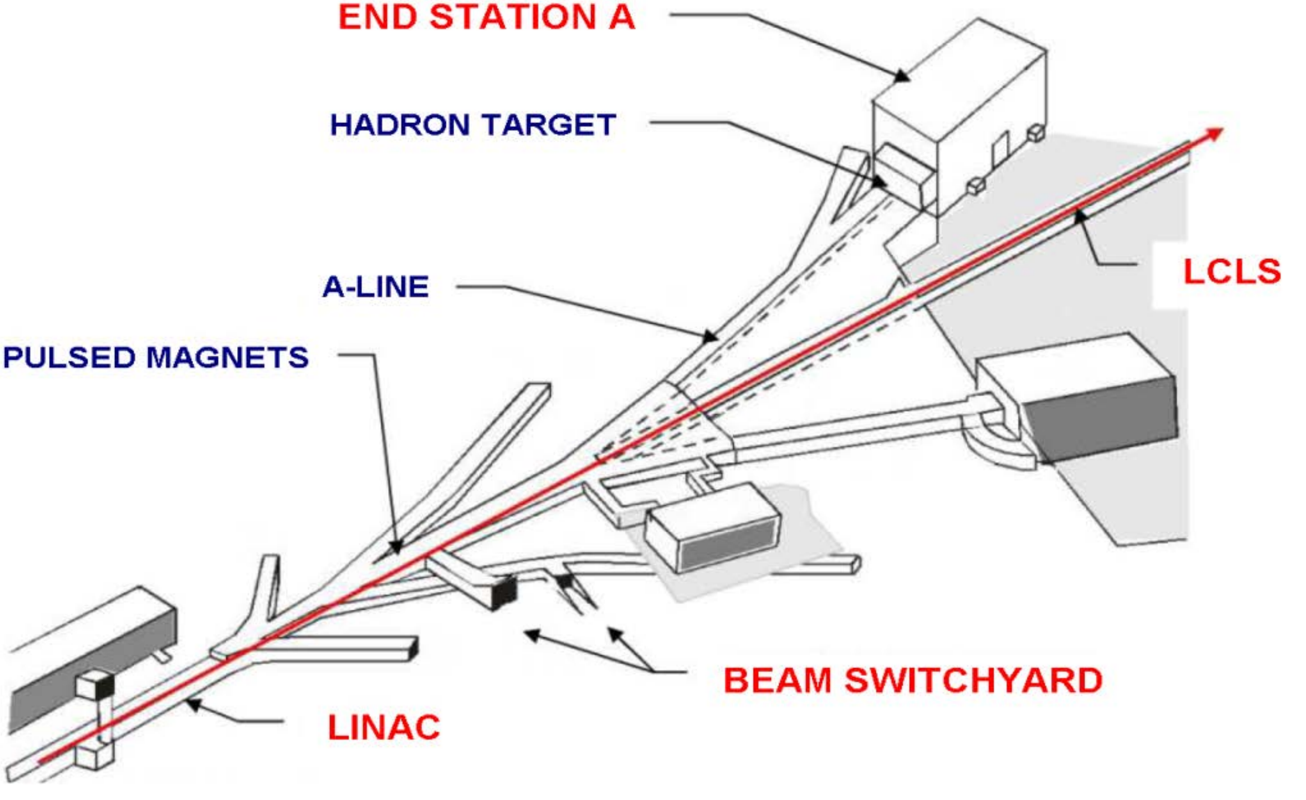
“Backstop” absorbs remaining power immediately downstream of sensor

➔ Realistic EM and hadronic doses in sensor, calibrated to EM dose

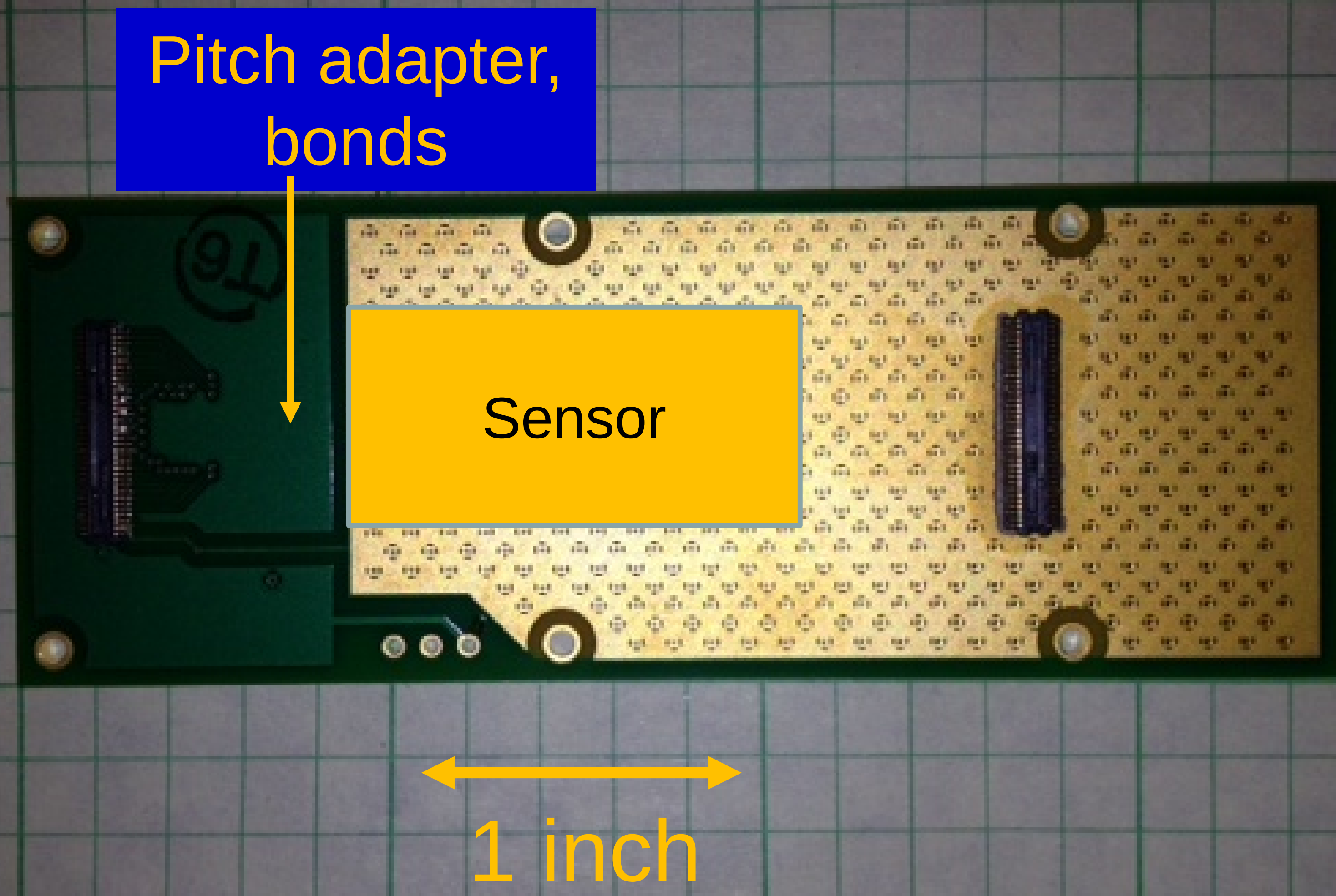
Irradiating the Sensors

LCLS and ESA

Use pulsed magnets in the beam switchyard to send beam in ESA.



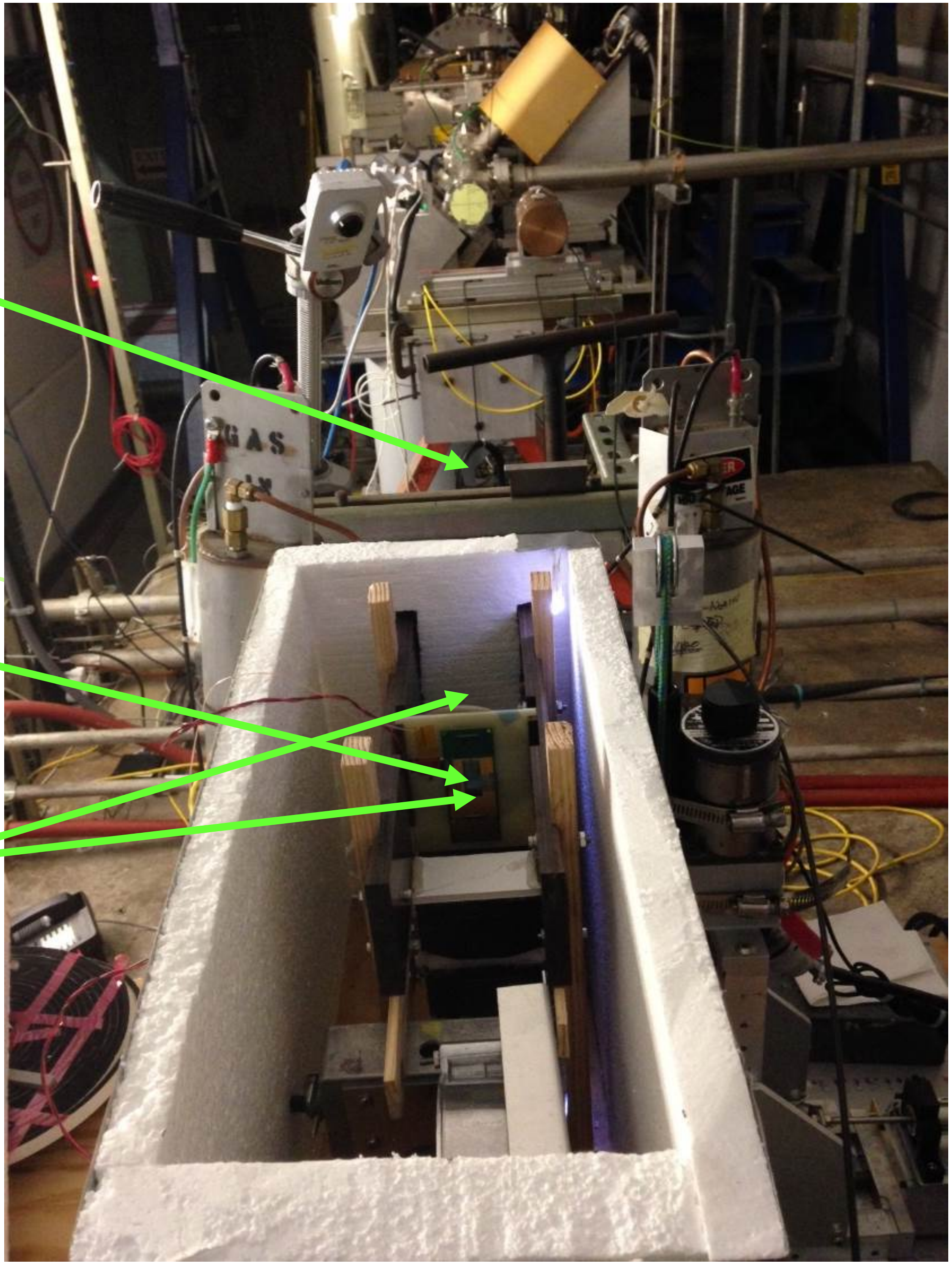
Daughter Board Assembly



2 X_0 pre-radiator; introduces a little divergence in shower

Sensor sample

Not shown: 4 X_0 “post radiator” and 8 X_0 “backstop”



Dose Rates (Including 1 cm^2 Rastering)

Mean fluence per incident e^-

Electron Energy (GeV)	Shower Conversion Factor α	Dose per nC Delivered Charge (kRad)
2	2.1	0.34
4	9.4	1.50
6	16.5	2.64
8	23.5	3.76
10	30.2	4.83
12	36.8	5.89

Confirmed with RADFET to within 10%

Maximum dose rate (e.g. 10.6 GeV; 10 Hz; 150 pC per pulse):

30 Mrad per hour

T506 Exposure History

Summer 2013: Initial Si Doses

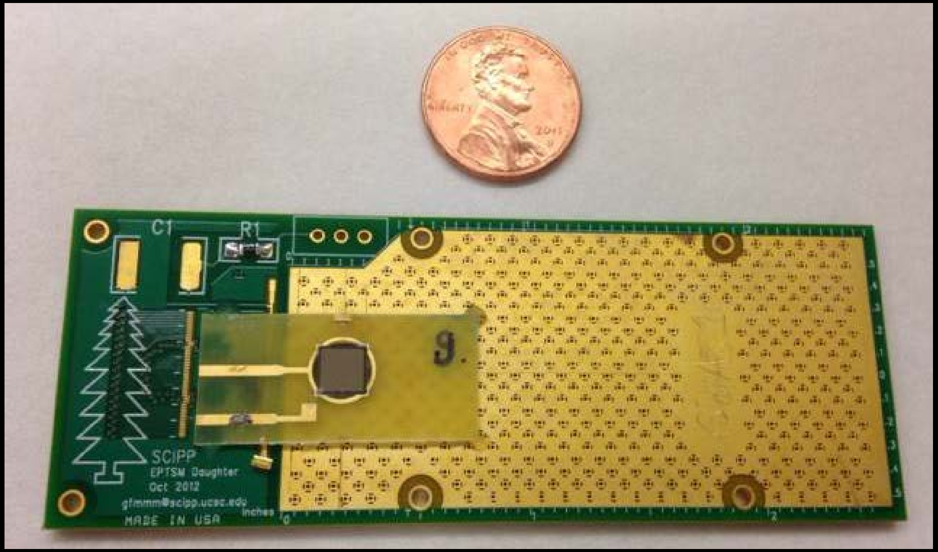
"P" = p-type "N" = n-type

"F" = float zone "C" = Czochralski

Sensor	V_{FD}	Irradiation Temp. (C)	Beam Energy (GeV)	Delivered Charge (μC)	Dose (MRad)
PF05	190	0	5.88	2.00	5.13
PF14	190	0	3.48	16.4	19.7
PC10	660	0	5.88	1.99	5.12
PC08	700	0	(5.88, 4.11, 4.18)	(3.82,3.33,3.29)	20.3
NF01	90	0	4.18	2.30	3.68
NF02	90	0	4.02	12.6	19.0
NF07	100	5	8.20	23.6	91.4
NC01	220	0	5.88	2.00	5.13
NC10	220	0	3.48	15.1	18.0
NC03	220	5	4.01	59.9	90.2
NC02	220	5*	(10.60,8.20)	(32.3,13.8)	220

Summer 2014: GaAs Doses

GaAs pad sensors via Georgy Shelkov, JINR Dubna

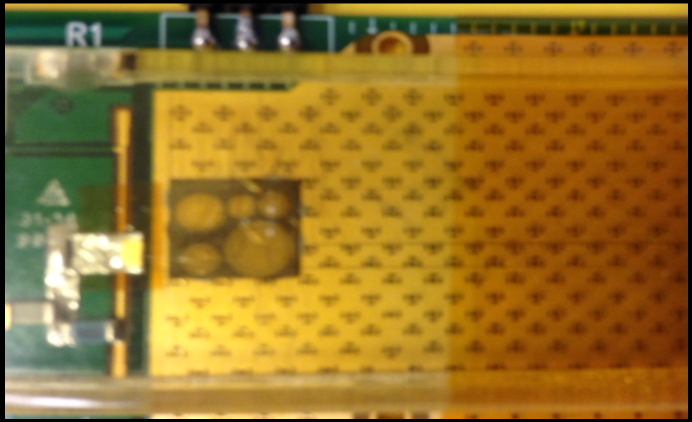


Irradiated with 5.7 and 21.0 Mrad doses of electromagnetically-induced showers

Irradiation temperature 3ºC; samples held and measured at -15ºC

Summer 2015: SiC and Further Si Exposure

SiC sensor array provided by Bohumir Zatko, Slovak Institute of Science



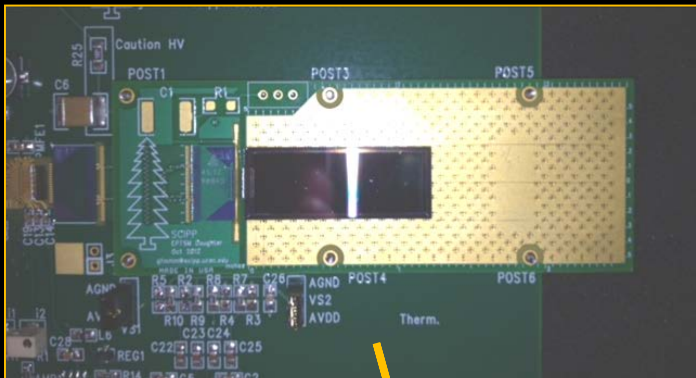
Irradiated to ~100 Mrad dose

Also, PF pad sensor irradiated to ~300 MRad

Assessing the Radiation Damage

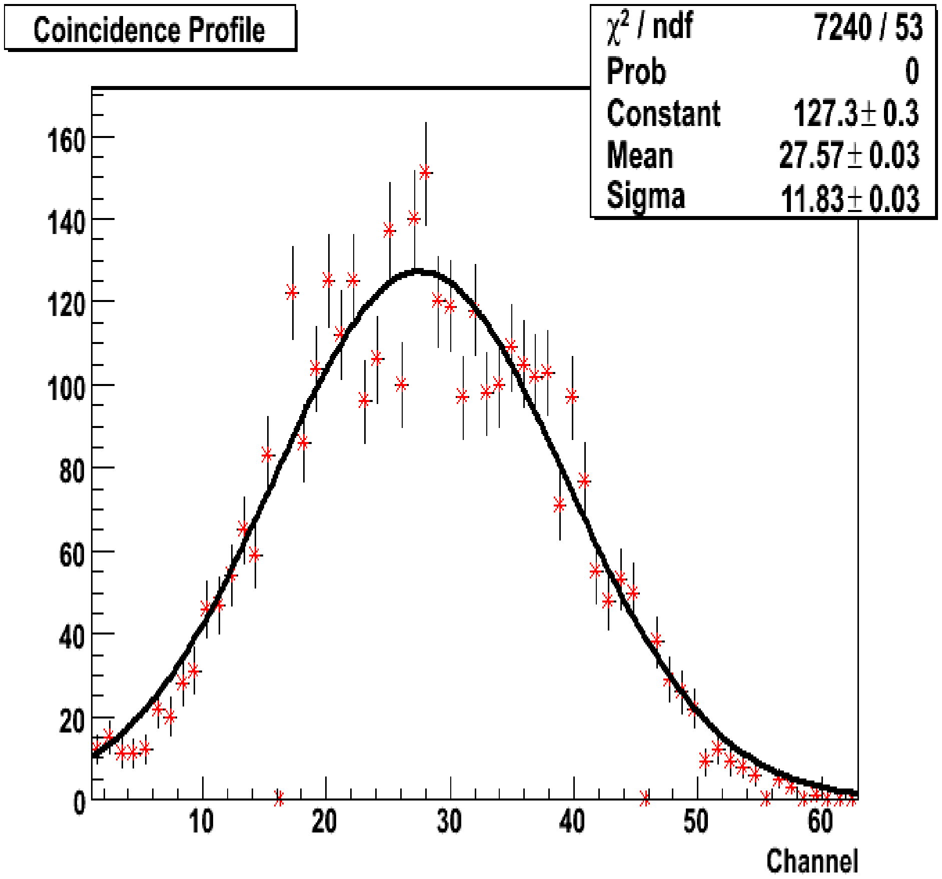
Charge Collection Apparatus

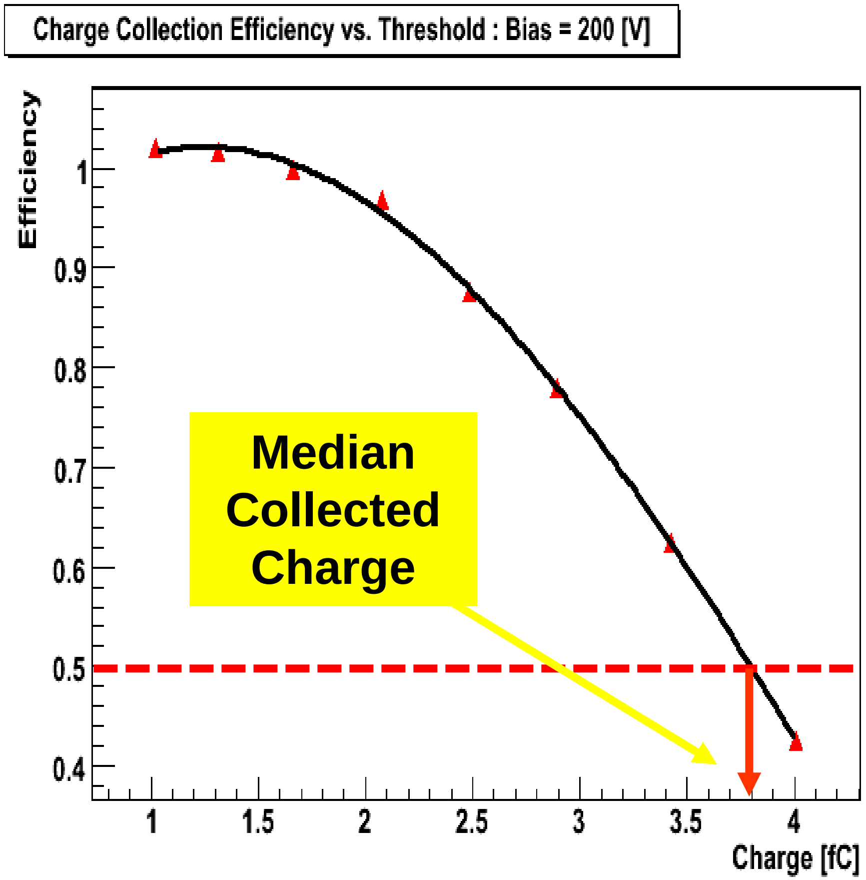
- **Readout: 300 ns**



Charge Collection Measurement

For strip sensors use multichannel readout



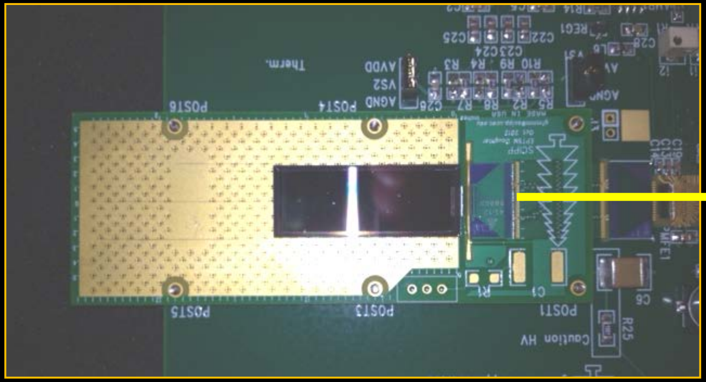


Channel-over-threshold profile

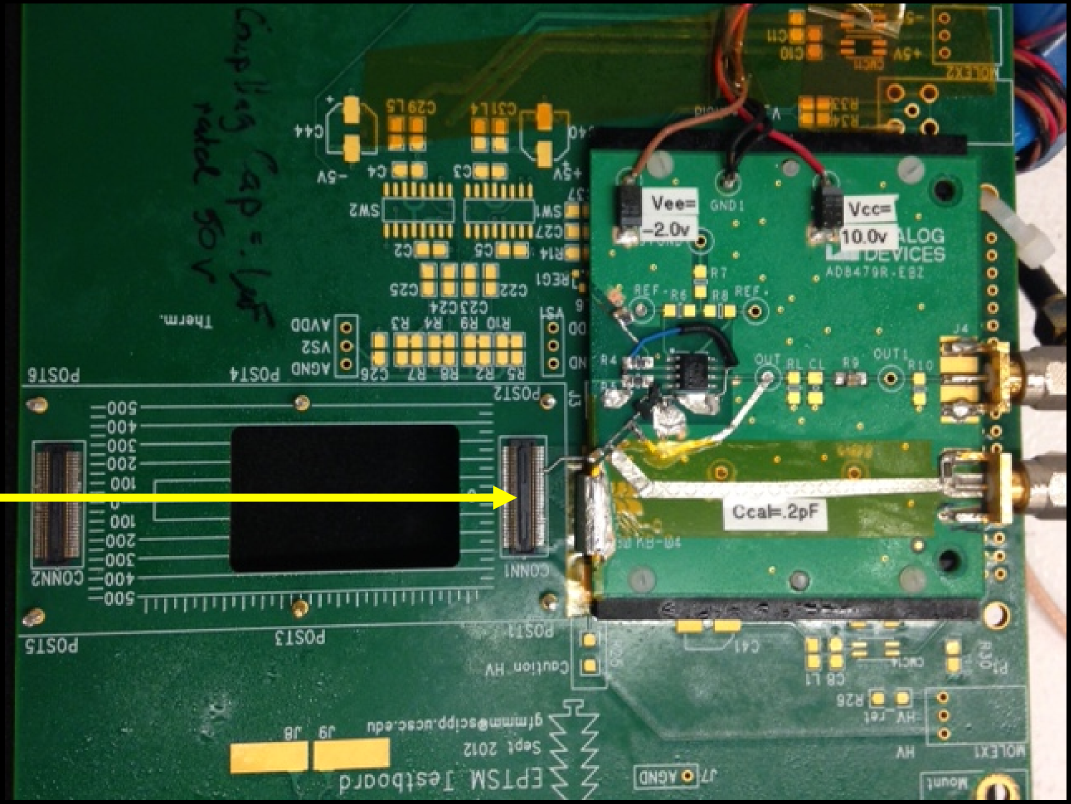
Efficiency vs. threshold

Charge Collection Measurement

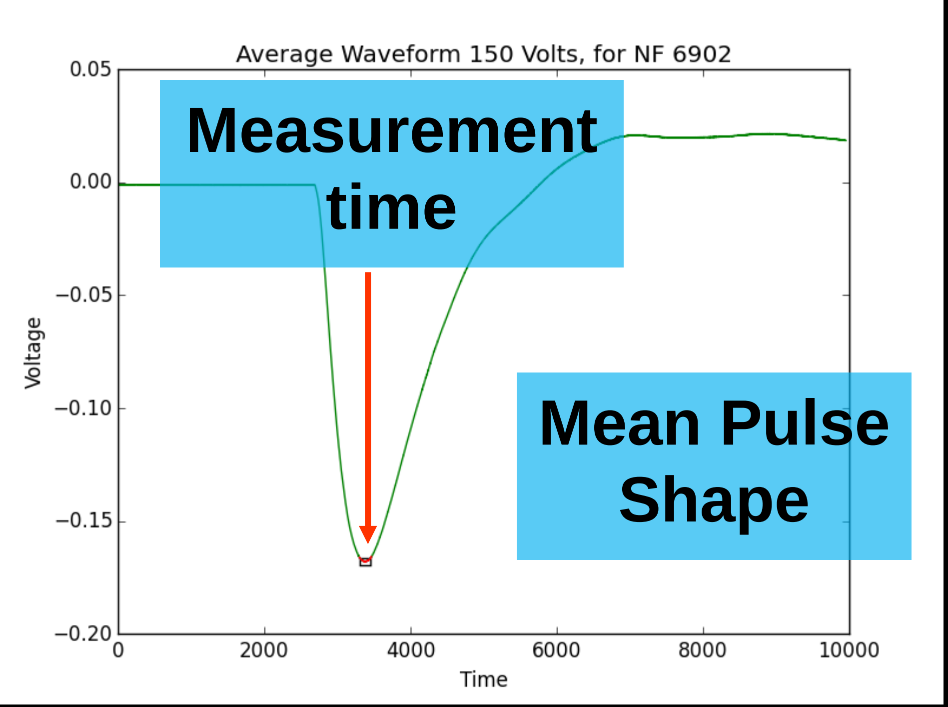
For pad sensors use single-channel readout

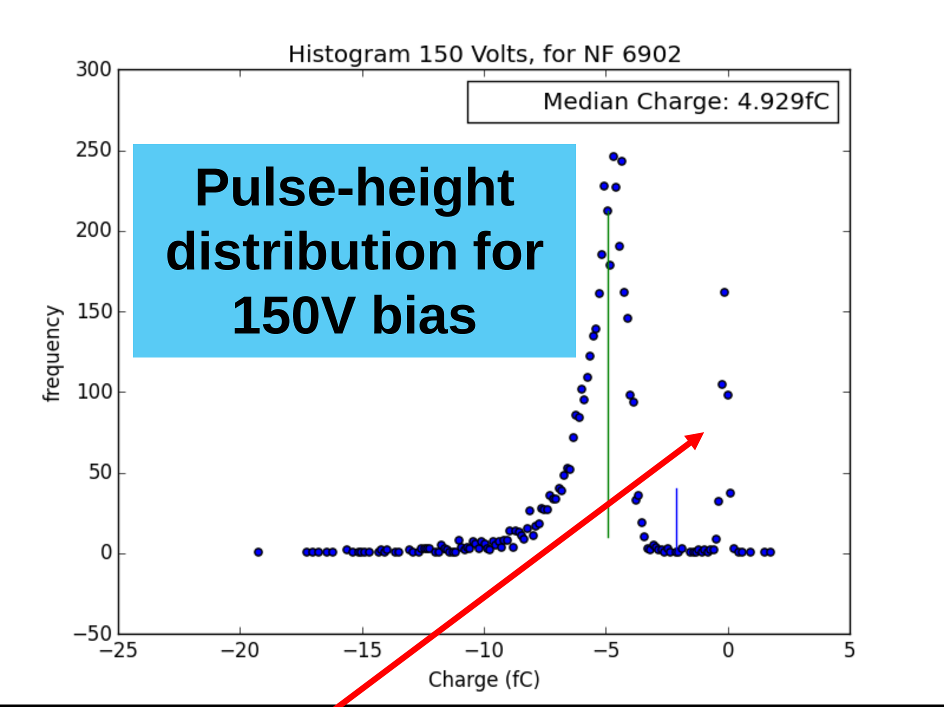


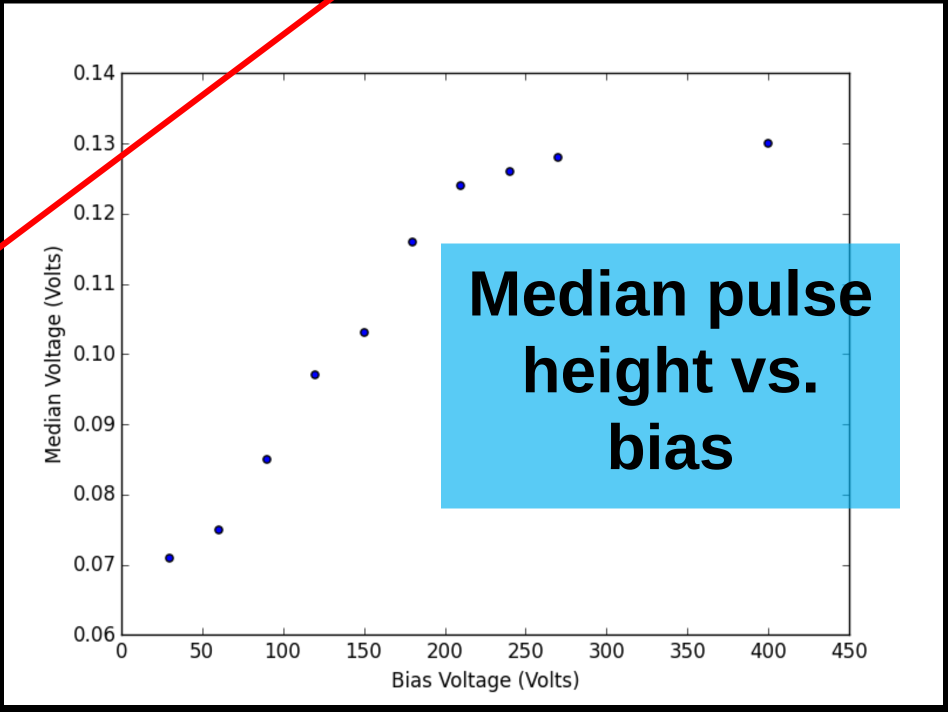
Daughter-board



Low-noise amplifier circuit (~300 electrons)





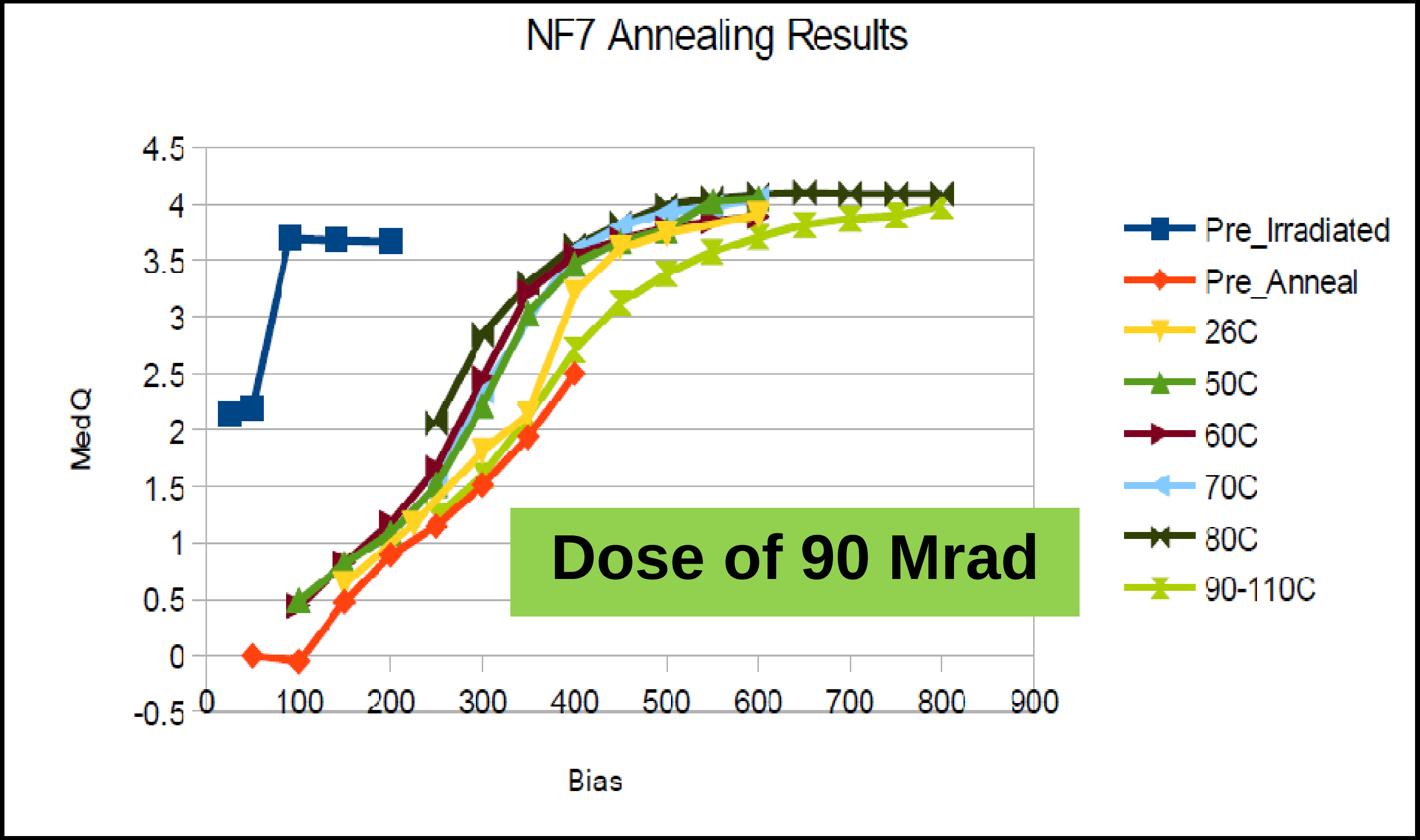


Single-channel readout example for, e.g., N-type float-zone sensor

Readout noise: ~300 electrons (plus system noise we are still addressing)

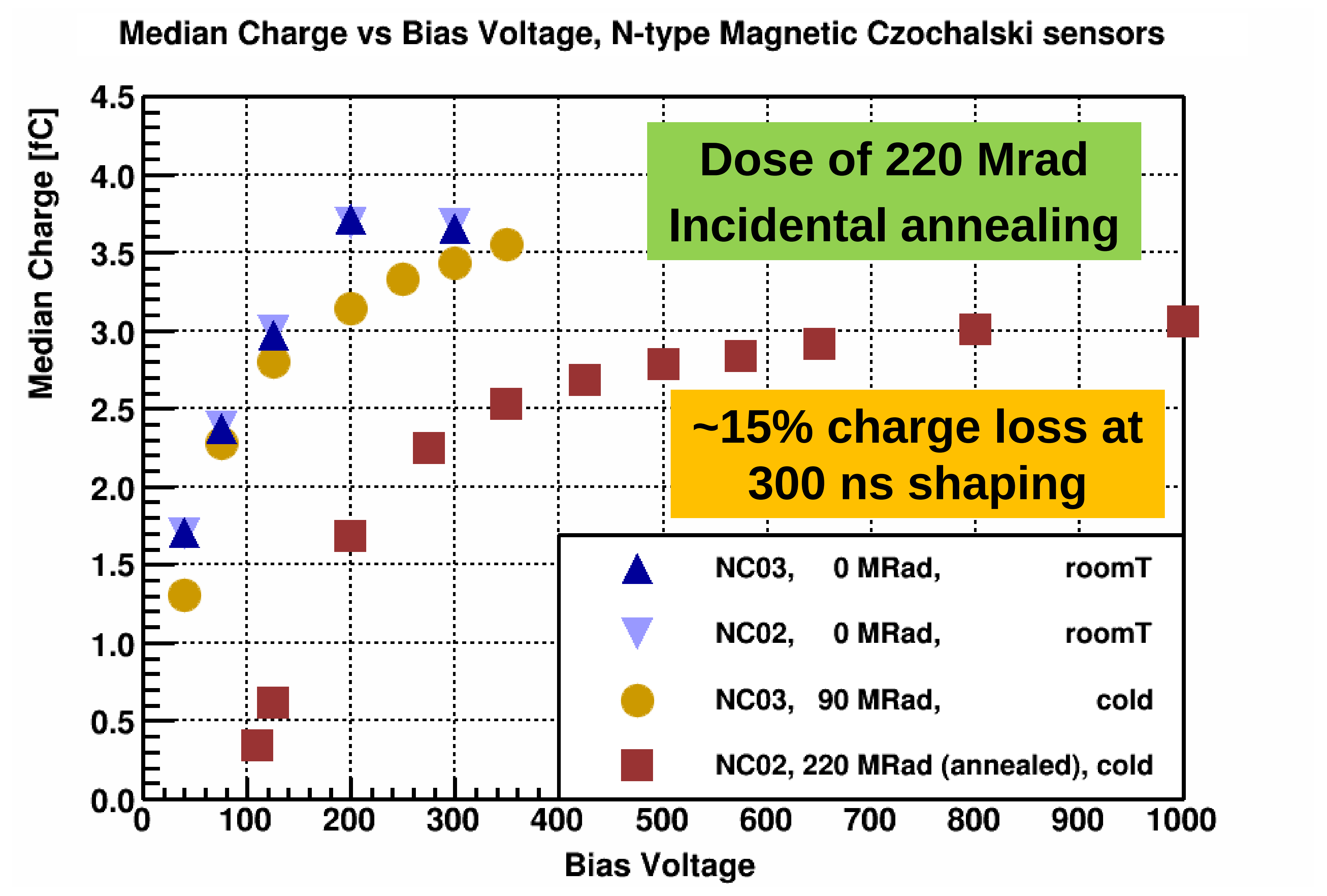
Results

Results: NF Sensor to 90 Mrad, Plus Annealing Study



Limited beneficial annealing to 90ºC (reverse annealing above 100ºC?)

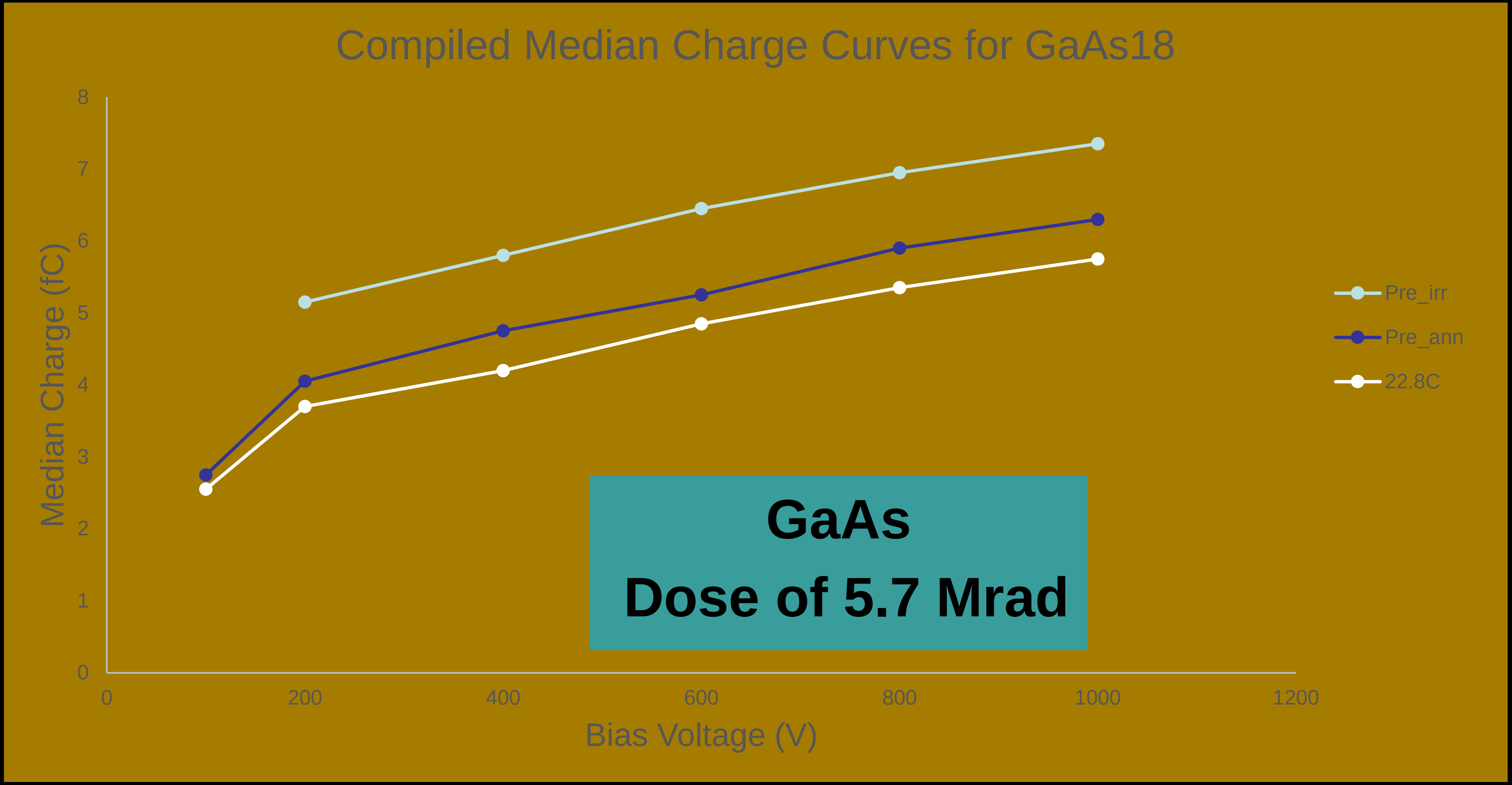
Results: NC sensors



GaAs

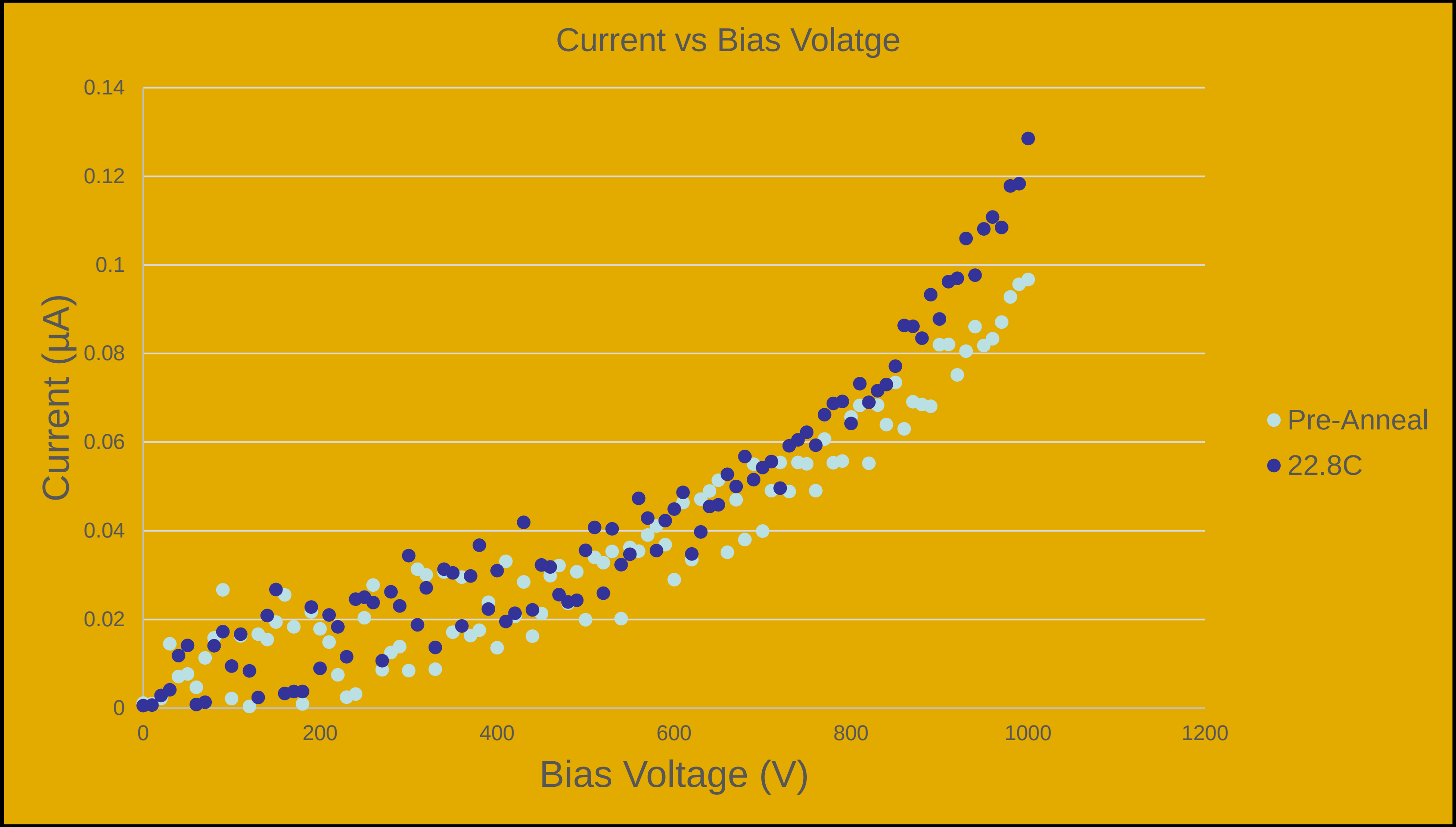
- 5.7 Mrad results
- 21 Mrad results are new

GaAs Charge Collection: 5.7 Mrad Exposure



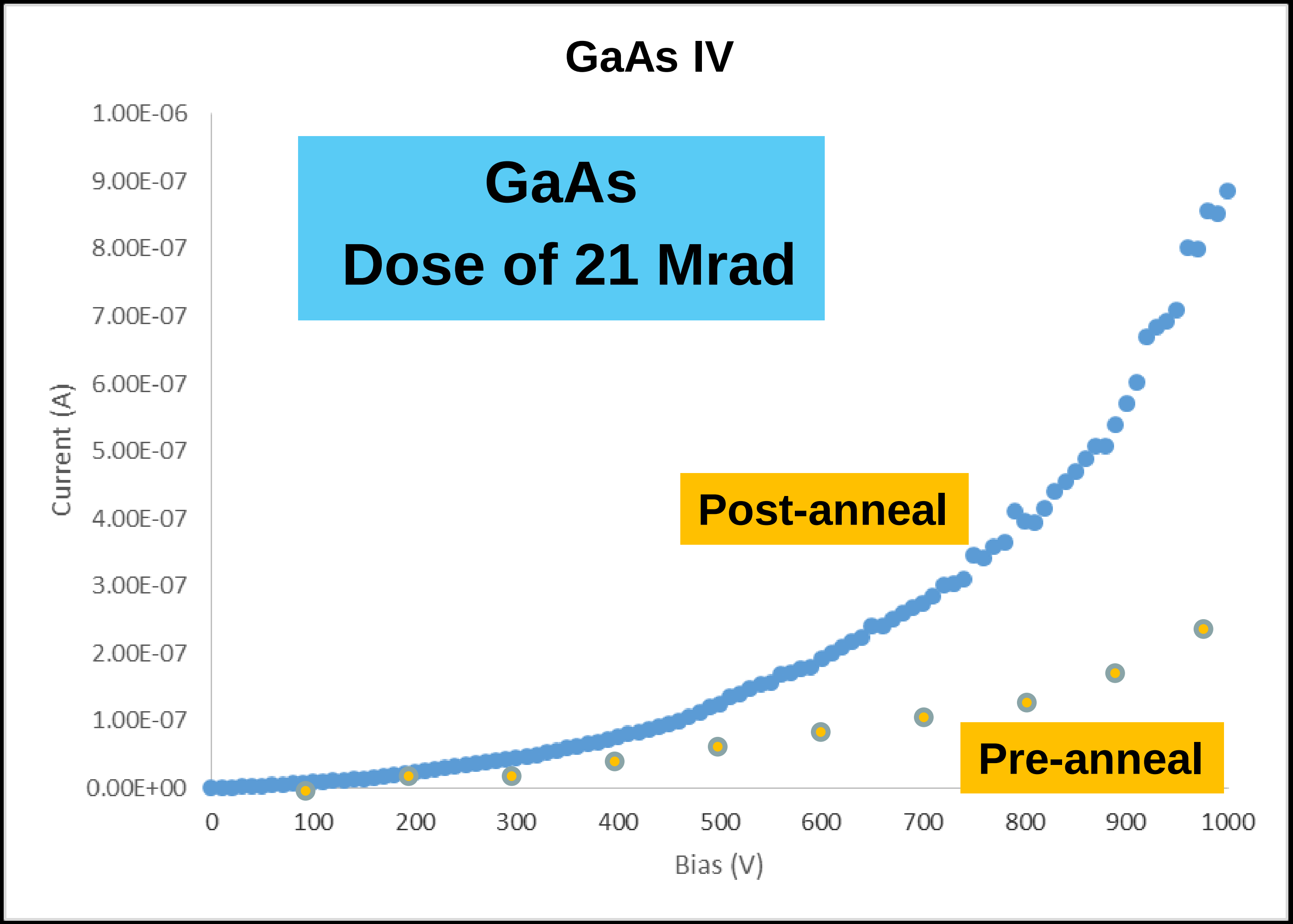
- 15-20% charge loss at 300 ns shaping
- Seems to worsen with annealing
- Sensor detached at 30º annealing step

GaAs Dark Current (-10^0 C)



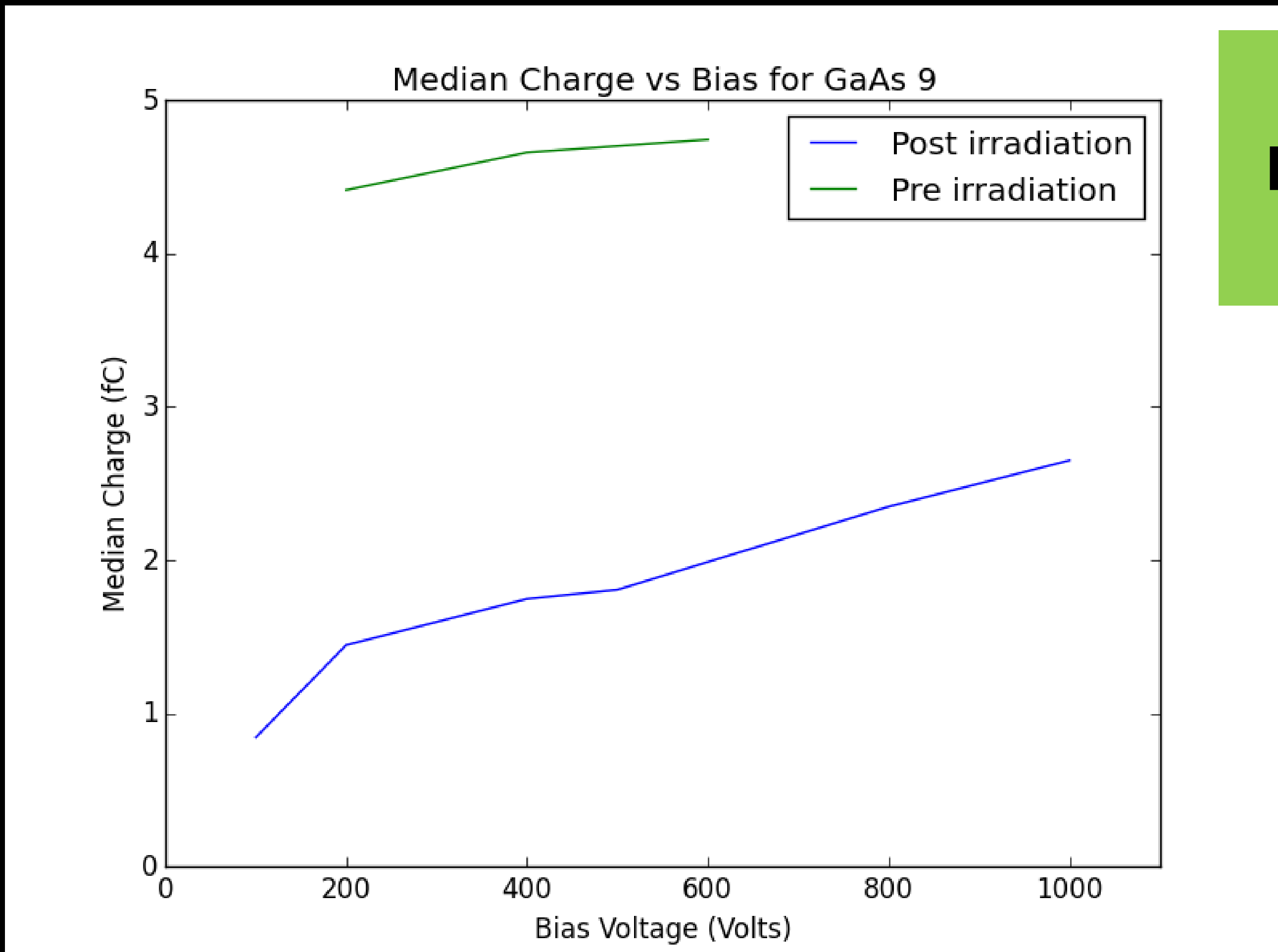
- O(100 nA/cm^2) after 6 MRad irradiation
- Not observed to improve with annealing

GaAs I-V after 21 Mrad Exposure (-10 C)



At 600 V, about 0.7 μA (0.0005 W) per cm^2

GaAs Charge Collection after 21 Mrad Exposure



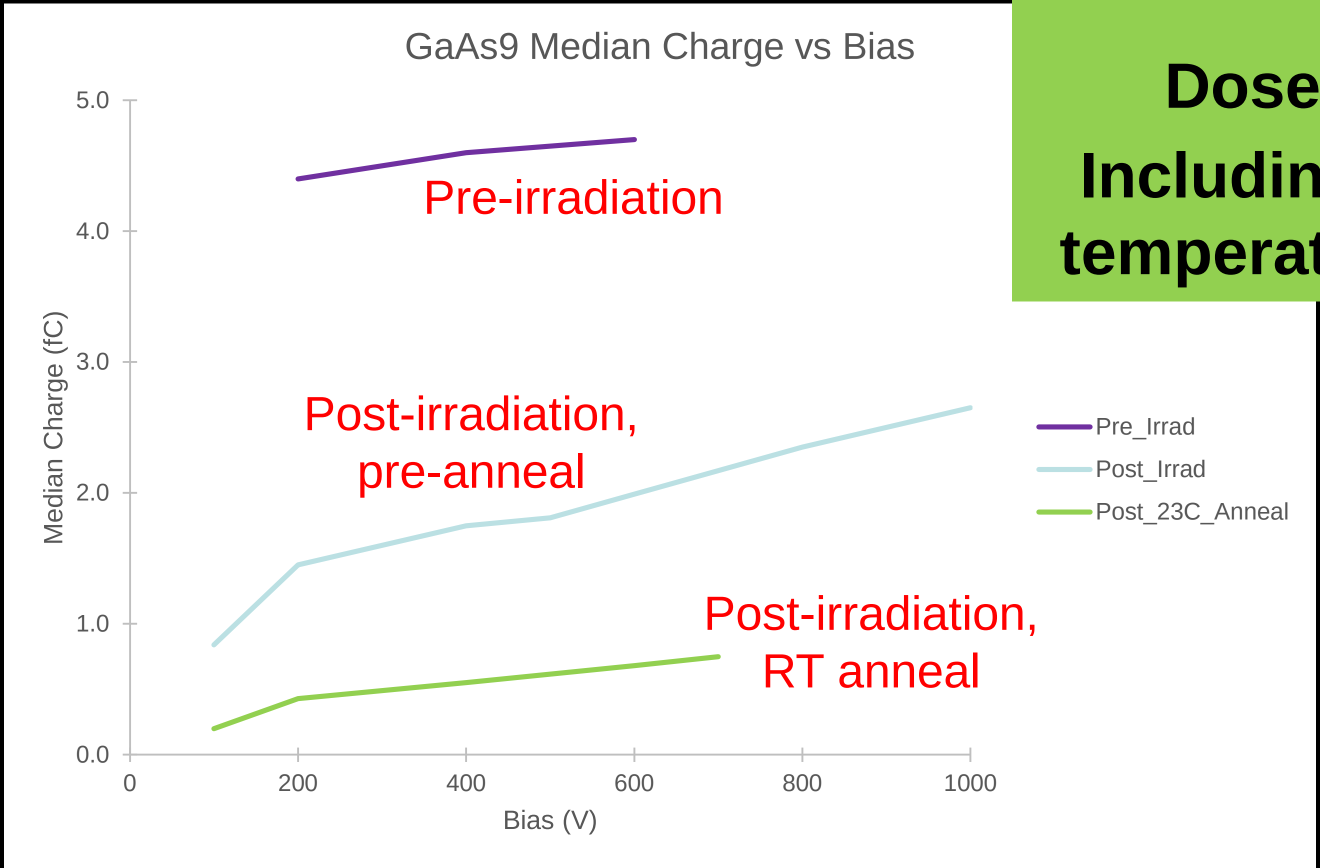
GaAs

Dose of 21 Mrad

No annealing

~60% charge loss at 300 ns shaping

GaAs Charge Collection after 21 Mrad Exposure and Room Temperature Annealing

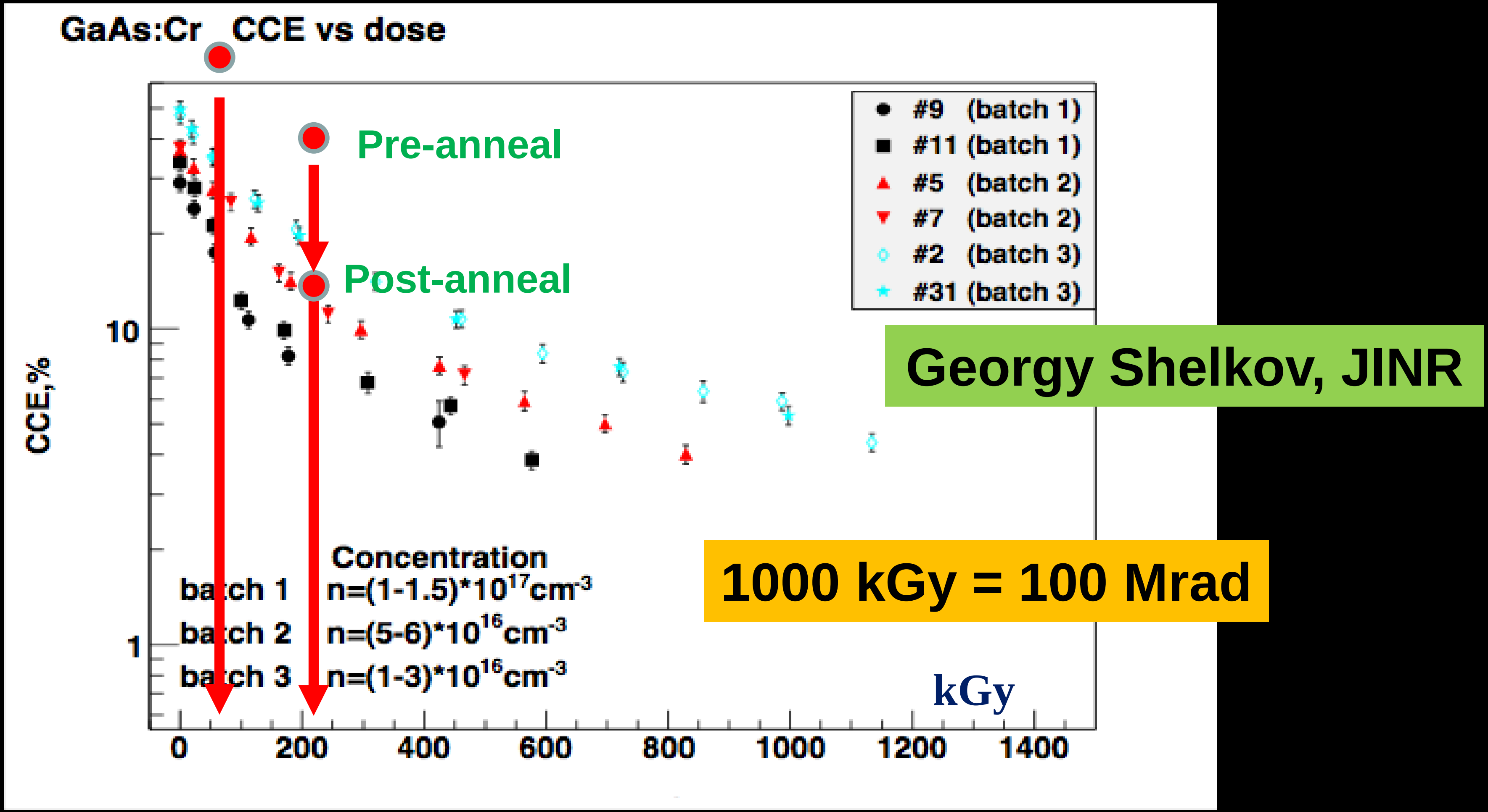


GaAs

Dose of 21 Mrad

Including 1 HR room-temperature annealing

Compare to Direct Electron Radiation Results (no EM Shower)

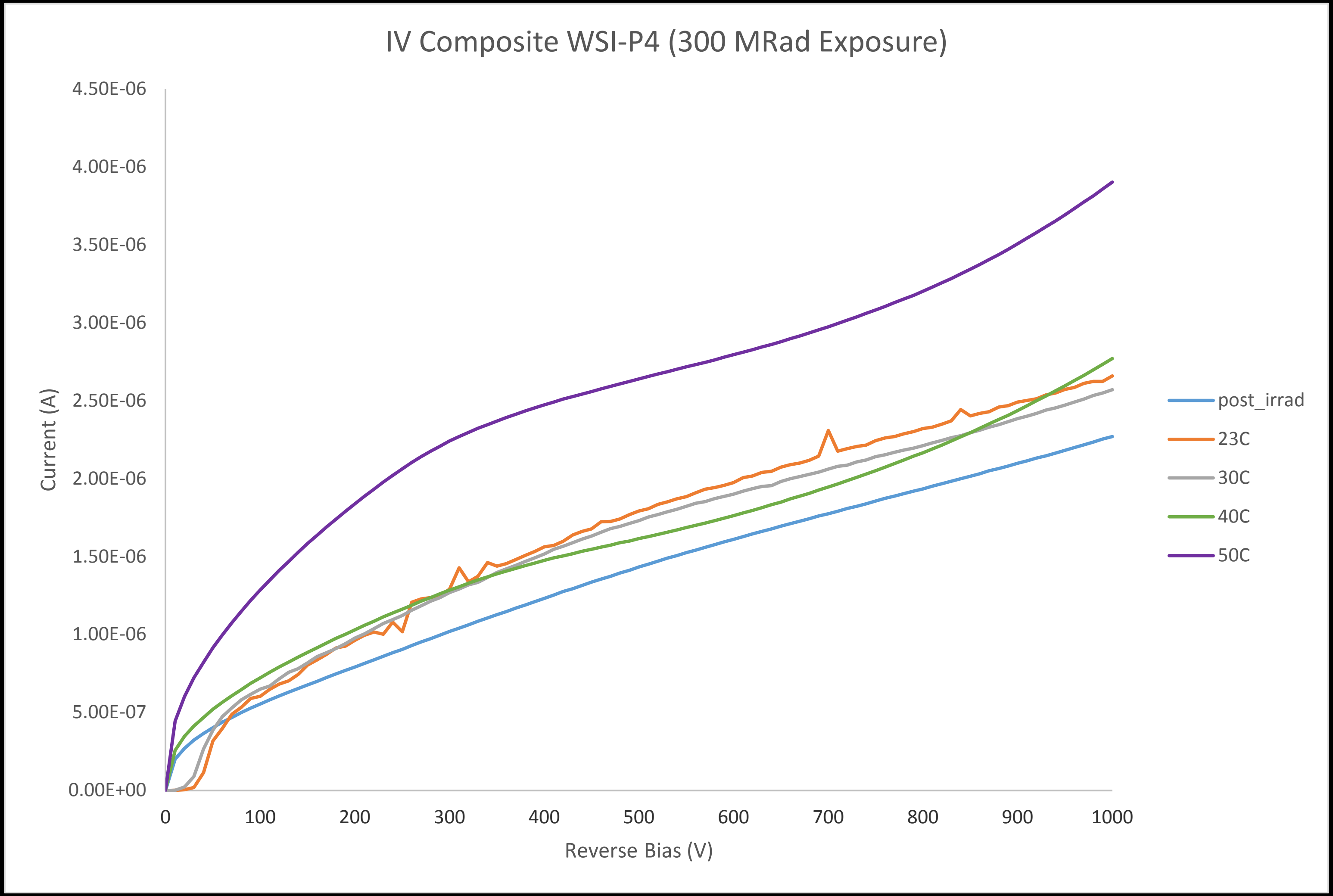


A bit better performance than direct result

P-Type Float-Zone Sensor

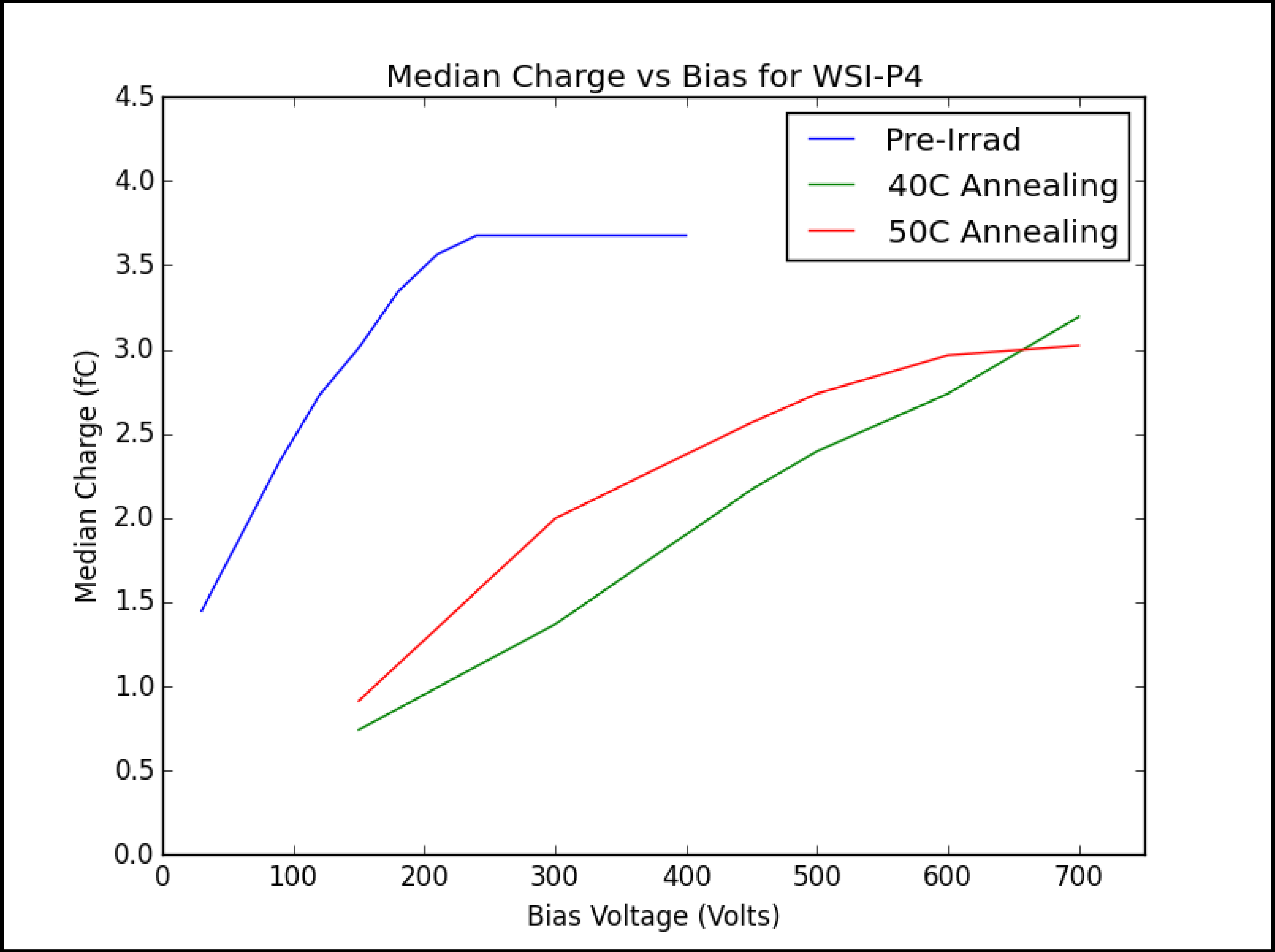
- New results for ~300 Mrad irradiation (about 3 years exposure)

NF I-V after 300 Mrad Exposure (-10 C)



At 600 V, about 75 μA (0.05 W) per cm^2 (sensor area ~ 0.025 cm^2)

NF Charge Collection after 300 Mrad



At 600 V, about 30% charge collection loss

Summary

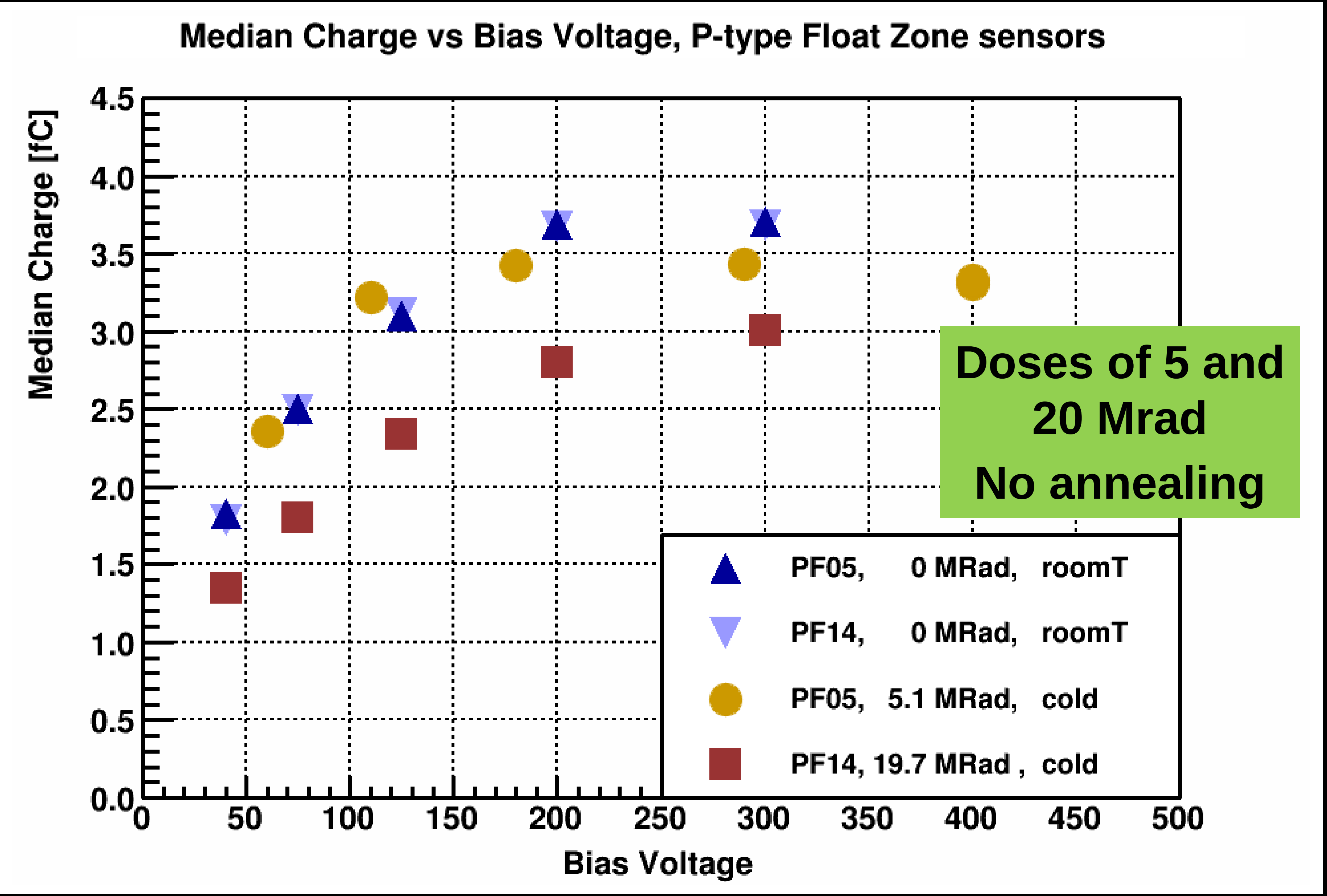
- Continuing program of study of radiation damage in a realistic EM shower environment
- Have irradiated and several Si sensors to as much as 300 Mrad, and GaAs to 20 Mrad.
- Si sensors show fair charge collection after ~3 years irradiation; of order 0.05W/cm^2 to bias
- GaAs charge loss significant at 6 Mrad and substantial at 21 Mrad. Significant loss from mild annealing. Explore further annealing…
- SiC sensor irradiated to 100 Mrad; awaiting I-V and CCE study
- System noise still a bit high for Sapphire

Looking Forward

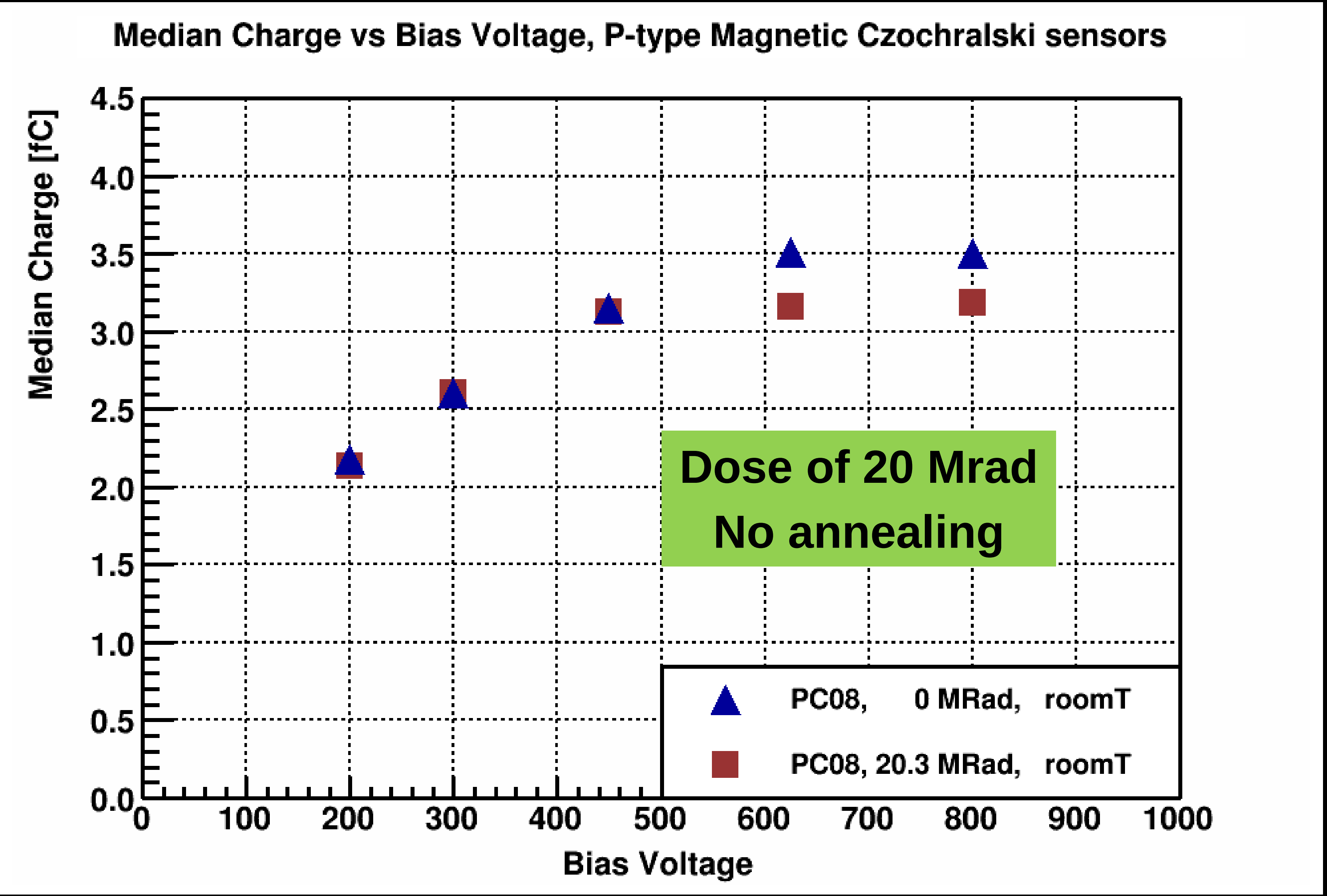
- 5-day x 24 hour run coming up in December
- Could be used for several 300 Mrad runs
- Will work on getting system noise down; perhaps Sapphire?
- May try higher exposure GaAs after exploring annealing
- May continue with SiC if performance at 100 Mrad is good
- December run plan not completely formulated yet

BACKUP

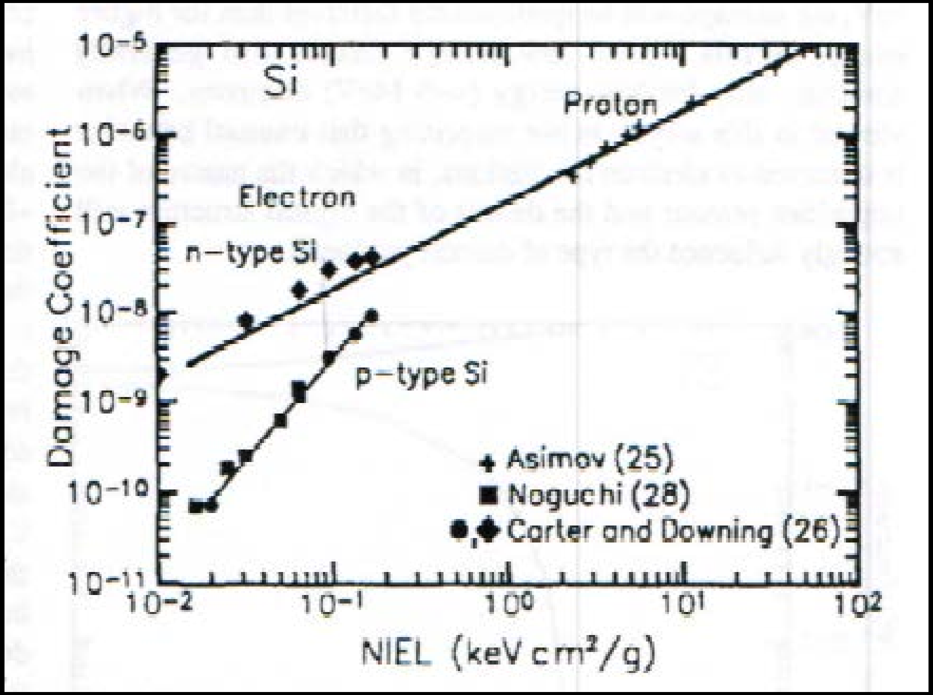
Results: PF sensors



Results: PC sensors



Departure from NIEL (non-ionizing energy-loss) scaling observed for electron irradiation



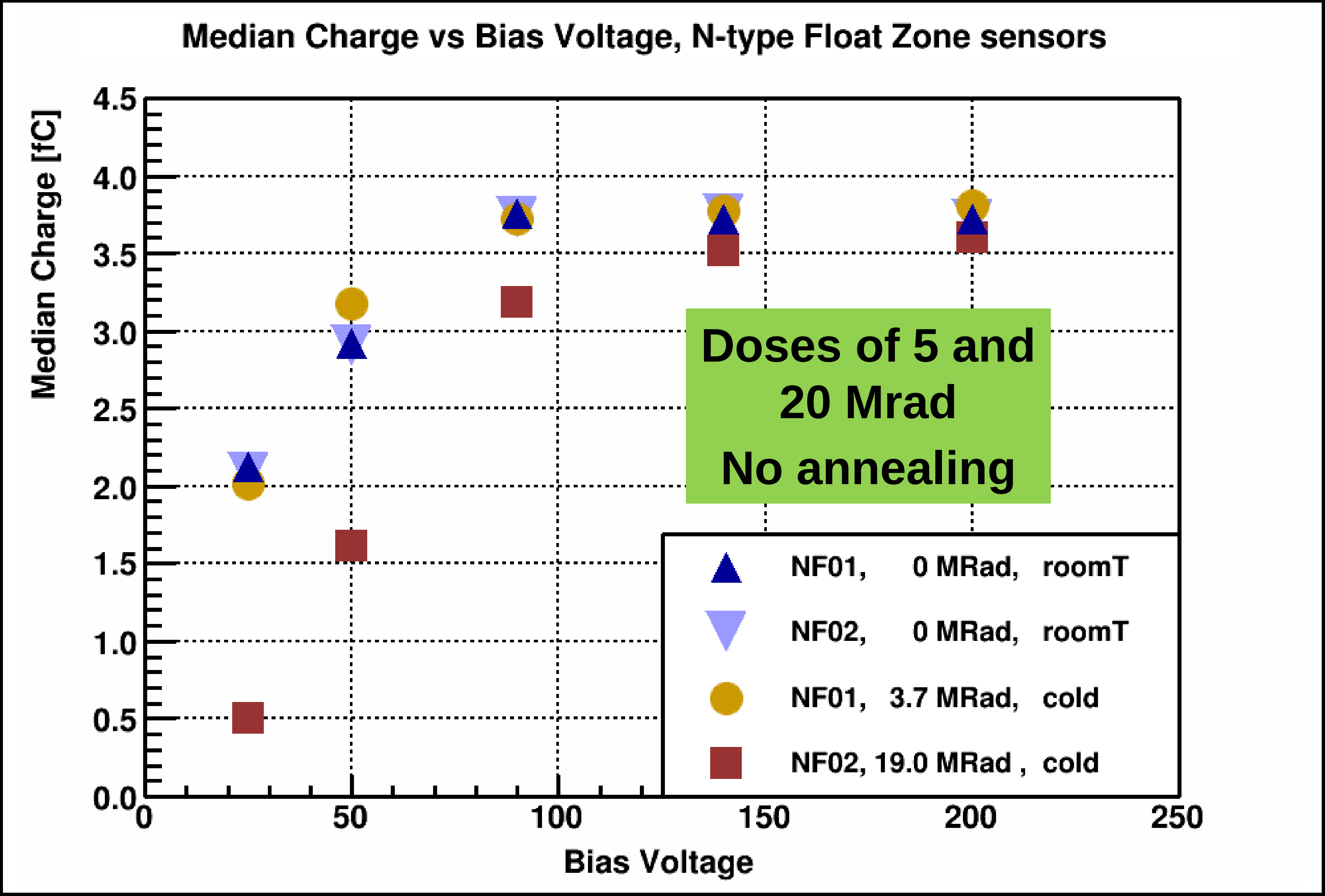
NIEL	e^- Energy
2×10^{-2}	0.5 MeV
5×10^{-2}	2 MeV
1×10^{-1}	10 MeV
2×10^{-1}	200 MeV

G.P. Summers et al., IEEE Trans Nucl Sci **40**, 1372 (1993)

Also: for ~50 MRad illumination of 900 MeV electrons, little loss of charge collection seen for wide variety of sensors [S. Dittongo et al., NIM A 530, 110 (2004)]

But what about the hadronic component of EM shower?

Results: NF sensor for low dose



Doses of 5 and 20 Mrad

No annealing